

THE NORTHERN ANDES:

A REVIEW OF THE ECUADORIAN PACIFIC MARGIN

John W. Baldock
(BGS)

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John W. Baldock

British Geological Survey

Keyworth, Nottingham NG12 5GG, England

[1]The Ocean Basins and Margins: Chapter 5

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I. INTRODUCTION

The territory of Ecuador includes an active oceanic spreading zone, the Galápagos or Cocos-Nazca Rift (Hey, 1977; Hey *et al.*, 1977), and an active subduction zone beneath the continental margin (Lonsdale, 1978; Feininger and Bristow, 1980). The mainland is dominated by the Andes, which attain altitudes of around 4000 m with isolated volcanoes up to a height of 6000m, and which divide the country into three natural, quite distinct, regions. To the east is the low-lying Oriente, part of the upper Amazon Basin. In the middle the comparatively narrow (100-150 km wide) Andean Mountain Belt, or Sierra, comprises the eastern Cordillera Real and Western Cordillera, separated by the inter-Andean valley and other discontinuous intermontane basins. The coastal zone, or Costa, includes various hill ranges close to the Pacific littoral as well as the extensive, low-lying, internal Guayas Basin, west of the Andes.

Offshore, a narrow continental platform and slope are terminated by the present-day submarine trench, which here barely reaches depths of 3000m. Beyond the trench the ocean floor is more uniform, but the transverse Carnegie Ridge is a prominent feature, especially where it joins the Cocos Ridge forming the Galápagos Platform (Holden and Dietz, 1972), on which the Galápagos Islands have been built up, constituting the fourth separate region of Ecuador, some 1000 km west of the mainland. South of the Carnegie Ridge lies the Carnegie Platform and Perú Basin; to the north is the complex Panama Basin (Lonsdale and Klitgord, 1978).

Systematic mapping of much of the Costa and Sierra of Ecuador during the last decade has led to a better understanding of the onshore geology and the publication of over 60 geological maps by the Dirección General de Geología y Minas, Quito, with the cooperation of the Institute of Geological Sciences, United Kingdom. The terminology, lithology, paleontology, age, thickness, and distribution of Ecuadorian stratal units, where known, has been comprehensively revised by Bristow and Hoffstetter (1977). Other publications arising from recent work include an outline of the geology of Ecuador (Kennerley, 1980), several detailed, specific studies such as Bristow (1973), Henderson (1979, 1981), Evans and Whittaker (1981), and Wilkinson (1982), as well as an annotated bibliography of Ecuadorian geology (Bristow, 1981) and a new edition (with summary explanation) of the national Geological Map of Ecuador (Baldock and Longo, 1982).

II. GEOLOGICAL FRAMEWORK

Ecuador is part of a type area, the whole western coast of South America, for active convergence of an oceanic plate with a continental lithosphere (Mitchell and Reading, 1969). Consequently, it is reasonable to suggest that a plate-tectonic regime was the dominant force in the development of the geological structure of the region, at least since Cretaceous times (Lonsdale, 1978; Feininger and Bristow, 1980), but little is known concerning the pre-Cretaceous history of the Costa and Sierra. The Proterozoic and Paleozoic (and early Mesozoic) geology of the Oriente (Tschopp, 1953) and of the proto-Cordillera (Kennerley, 1980) could have been related to the development of a foldbelt on the margin of the Archean Guyana Craton (Engel *et al.*, 1974*;* Fig. 12) followed by diastrophism as a result of polyphase (late Mesozoic-Pliocene) Andean Orogeny. Precambrian and Paleozoic tectonism may or may not have depended on subduction processes for its driving force (Engel *et al.*, 1974), whereas Andean tectonism almost certainly was the result of, or response to, such forces.

The transverse tectonic segmentation of the Andean chain into regions with differing characteristics is particularly marked between the Central and Northern Andes (Gansser, 1973; Sillitoe, 1974). Here, at the diffuse Huancabamba deflection (Ham and Herrera, 1963), the Andean strike alters from NW in northern Perú, to NNE in Ecuador (see Fig. 2). This is reflected in the change at the Guayaquil-Dolores Suture, or Megashear (Case *et al.*, 1971; Shepherd and Moberly, 1975), from an ensialic basement in the south, with felsic metamorphic and abundant plutonic rocks close to the Pacific margin, to a northern ensimatic province, comprising Cretaceous basalts with no sialic basement near the coast (Feininger, 1977; Henderson, 1979; Feininger and Bristow, 1980; Shepherd and Moberly, 1981). Another segment boundary may occur in northern Ecuador, offsetting the Cretaceous volcanics of the Western Cordillera (see Fig. 2).

A. Geology of the Oriente

The Oriente represents part of the pericratonic (foreland) platform, or laterally a back-arc basin, developed between the Guyana Craton and the Cordilleran Orogenic Belt, a tectono-sedimentary environment stretching from Venezuela to Bolivia on the east of the Andes (Tschopp, 1956; Harrington, 1962). The Oriente Basin of Ecuador was divided into two structural provinces in the late Tertiary when the sub-Andean zone (see Fig. 4), which partly corresponds to the Eastern Cordillera of Colombia, was subjected to Andean tectonism. The whole region is probably underlain at depth by crystalline rocks of the Guyana Shield (Campbell, 1970), which is exposed in southeastern Colombia (INGEOMINAS, 1976), but is covered by a thick epicontinental sedimentary sequence (see Fig. 1) in Ecuador (Tschopp, 1953).

Unmetamorphosed Paleozoic rocks crop out only in an isolated antiformal structure in the Cordillera de Cutucú in the southern sub-Andean region (Tschopp, 1953). The succession is at least 2500 m thick and comprises black argillites and sandstones (Pumbuiza Formation, probably of Devonian age) overlain by limestones and shales (Macuma Formation) of Carboniferous age (Sigal, 1968). Their extent beneath the thick Mesozoic-Tertiary cover is unknown, but they may occur as widespread but thin (~1000 m) platform deposits directly overlying the ancient Precambrian basement in some areas. Metamorphosed (and deeper-water?) equivalents of these Paleozoic formations may form parts of the Cordillera Real. Tschopp (1948) and more recently Mortimer (1980a) have correlated the weakly metamorphosed black slates and phyllites of the Margajitas Formation occurring in a narrow belt along the eastern flank of the Cordillera Real with the Pumbuiza. However, Bristow and Hoffstetter (1977) have pointed out that the Margajitas might equally well be correlated with the Napo Formation (see p. 4). It apparently passes southward into unmetamorphosed, undifferentiated, Cretaceous sediments (Limón Group) (Baldock and Longo, 1982).

CORRELATION CHART

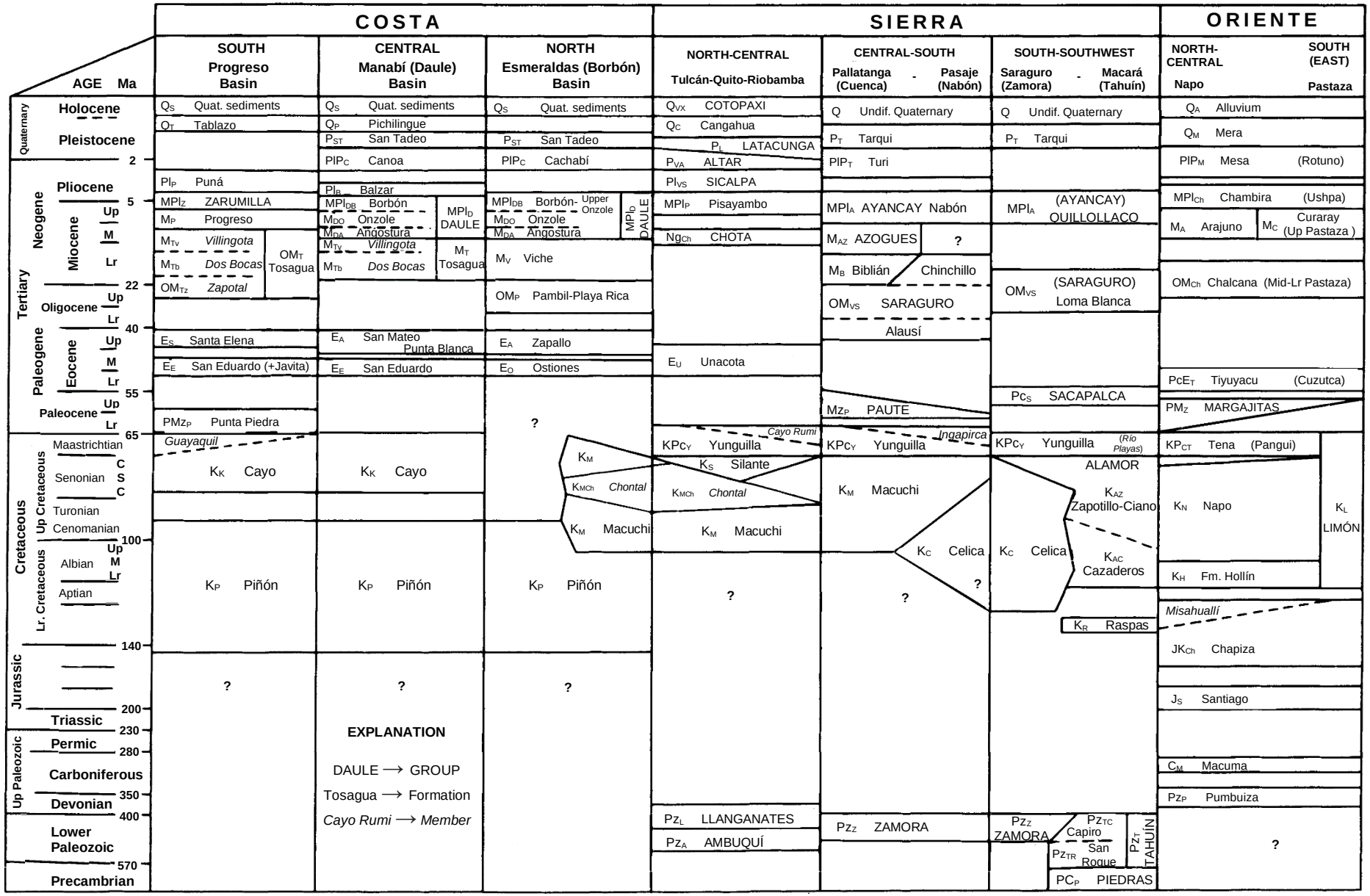


Fig 1. Correlation chart. K_P: symbol composed of system letter (U) and stratigraphic name (P). See text.

A sequence of Mesozoic-Tertiary sediments, some 8-12 km thick, was deposited in the Oriente Basin by a succession of sedimentary cycles (Campbell, 1974). Marine conditions prevailed during deposition of the Lower Jurassic (Sinemurian) Santiago Formation, represented by 2500 m of shelf lime-stones, sandstones, and shales. This sequence is restricted to the southern half of the Ecuadorian Oriente (Cutucú Uplift), although southward it can probably be correlated with part of the much more extensive Pucará Group in Perú (Cobbing *et al.*, 1981). The unconformably overlying Upper Jurassic to lowermost Cretaceous Chapiza Formation, which varies from 1000 to 4500 m in thickness, comprises red-bed sandstones and shales with intercalated pyroclastics. Andesitic lavas with subordinate pyroclastics (Misahuallí Member) become dominant in the upper part of the sequence in the northern Oriente (Tschopp, 1956). Three major fault-bounded batholiths (Zamora, Abitagua, and Cuchilla) probably of middle Jurassic age (Hall and Calle, 1982) were emplaced along the extreme western margin of the belt, at its thrust-faulted contact with the metamorphic rocks of the Cordillera Real (Fig. 3). Subvolcanic rocks of the Guacamayos Series (Tschopp, 1953) may be related to this magmatic episode.

A widespread Cretaceous marine transgression was heralded by deposition of thin epicontinental sandstones (Hollín Formation), and succeeded by the thick limestone-shale sequence of the (miogeosynclinal) Napo Formation, which is now thought to be of Albian to Campanian or even middle Maastrichtian age (Whittaker and Hodgkinson, 1979; Wilkinson, 1982). Clastic material was derived almost entirely from denudation of the Guyana Craton to the east. Wilkinson (1982) has summarized the evidence for postulating a proto-Andean (Cordillera Real), but not necessarily emergent, positive feature as proposed by Sauer (1965) and Campbell (1970), dividing the miogeosynclinal Napo Basin from the continental margin basin, and island arc, to the west. His paleogeographic lithofacies map (Wilkinson, 1982; Fig. 2 therein) reproduced here as Fig. 8, is based on a detailed analysis of the facies variations, including much unpublished data from oil exploration (Kehrer, 1975), within the Napo (see also Wilkinson, 1982, Figs. 3, 4, 5 therein): It supersedes Kennerley's (1980; Fig. 3 therein) earlier interpretation (reproduced here as Fig. 9), which suggested the presence of a hinge line to deeper open-water conditions, as also proposed by Feininger (1975).

Red-bed shales, sandstones, and marls of Maastrichtian-Lower Paleocene age (Tena Formation) unconformably overlie the Napo, testifying to a marine regression and showing an increasing derivation of clastic material from the west. By the end of the Cretaceous the proto-Cordillera Real had become an emergent feature providing a source of sediment for both the Oriente Basin and the continental margin basin to the west (Kennerley, 1980, Fig. 4 therein, reproduced as Fig. 10 in this chapter)-as it continued to do for much of the Tertiary. The Tena thins from 600 m in the west to 270 m in the eastern Oriente (Faucher and Savoyat, 1973; Feininger and Bristow, 1980). In the southern part of the Oriente Basin equivalent red-bed sediments were originally denominated as the Pangui Formation (Tschopp, 1953; Bristow and Hoffstetter, 1977), but recent mapping and compilation (Mortimer, 1980b; Baldock and Longo, 1982) has extended the northern terminology to the whole basin.

The thick Tertiary sequence comprises a series of mainly continental clastic units that show a slight facies variation between the northern (Napo) basin and the southern (Pastaza) basin (Tschopp, 1953). The Tena Formation is unconformably overlain by Paleocene-Lower Eocene conglomerates, sandstones, and shales of the Tiyuyacu Formation (Cuzutca in the SE Oriente), but no deposits of middle Eocene-Upper Oligocene age have been documented. The uppermost Oligocene-Lower Miocene Chalcana Formation consists of red-bed shales with gypsum deposits (Tschopp, 1953). This in turn is overlain by Miocene brackish-water clays, sandstones, and lignites of the Arajuno Formation, with the continental Curaray facies (red clays, tuffaceous shales, and gypsum) in the south and east of the Oriente Basin. Mio-Pliocene sandstones, shales, and tuffs (Chambira Formation), were tilted and warped before deposition of the Plio-Quaternary piedmont/mesa conglomerates, sandstones, and volcaniclastics derived from the uplifted Sierra.

The Oriente Basin of Ecuador deepens northward and more evidently southward from the central E-W trending Cononaco Arch (Fig. 4) (Wilkinson, 1982; Fig. 3 therein, reproduced as Fig. 7 in this chapter). It is principally along the main N-S axis of this back-arc basin that the oil fields of northeastern Ecuador have been discovered (Kehrer, 1975; Zúñiga y Rivero *et al.*, 1976). The trough is bounded to the west by the fold/thrustbelt of the sub-Andean zone (Fig. 2), which was subjected to Tertiary deformation, and which is characterized by high-angle thrust faults and steep to open folds (Fig. 5; sections 6 and 7). Subsequent uplift and erosion have led to exposure of folded Upper Paleozoic-Tertiary (Miocene) rocks, originally deposited on the western edge of the miogeosynclinal Oriente Basin, which are partly covered by Plio-Quaternary piedmont deposits from the uplifted Cordillera.

B. Geology of the Sierra

The Sierra of Ecuador is divided into two parallel, geologically distinct, zones trending NNE. Metamorphic rocks of various ages underlie the Cordillera Real, whereas mainly marine Cretaceous to Paleogene volcanic and subsidiary sedimentary rocks comprise the bulk of the Western Cordillera (Fig. 2). Neogene volcanics cover parts of both ranges and infill the inter-Andean valley, which separates the two Cordillera, although in the south the distinction is morphologically less obvious. The southwestern part of the country (south of the Jubones Fault, see Fig. 2) is quite different, having a pre-Mesozoic metamorphic basement (Tahuín block) overlain by Cretaceous volcanics and sediments (Kennerley, 1973).

1. Cordillera Real

A major zone of high-angle thrust faulting, running the entire length of Ecuador, separates the sub-Andean back-arc foldbelt of the Oriente from the metamorphic rocks of the Cordillera Real (SNGM, 1969; Baldock and Longo, 1982), Parts of the flanks of this belt are evidently underlain by Mesozoic phyllites, schists, and metavolcanics: the Margajitas Group on the eastern flank may represent metamorphosed Cretaceous shales (p. 2, 4) and a transition from fossiliferous Maastrichtian shales (Yunguilla Formation) and volcanics into schists and metavolcanics of the Paute Group has been reported east of Cuenca (Bristow, 1973).

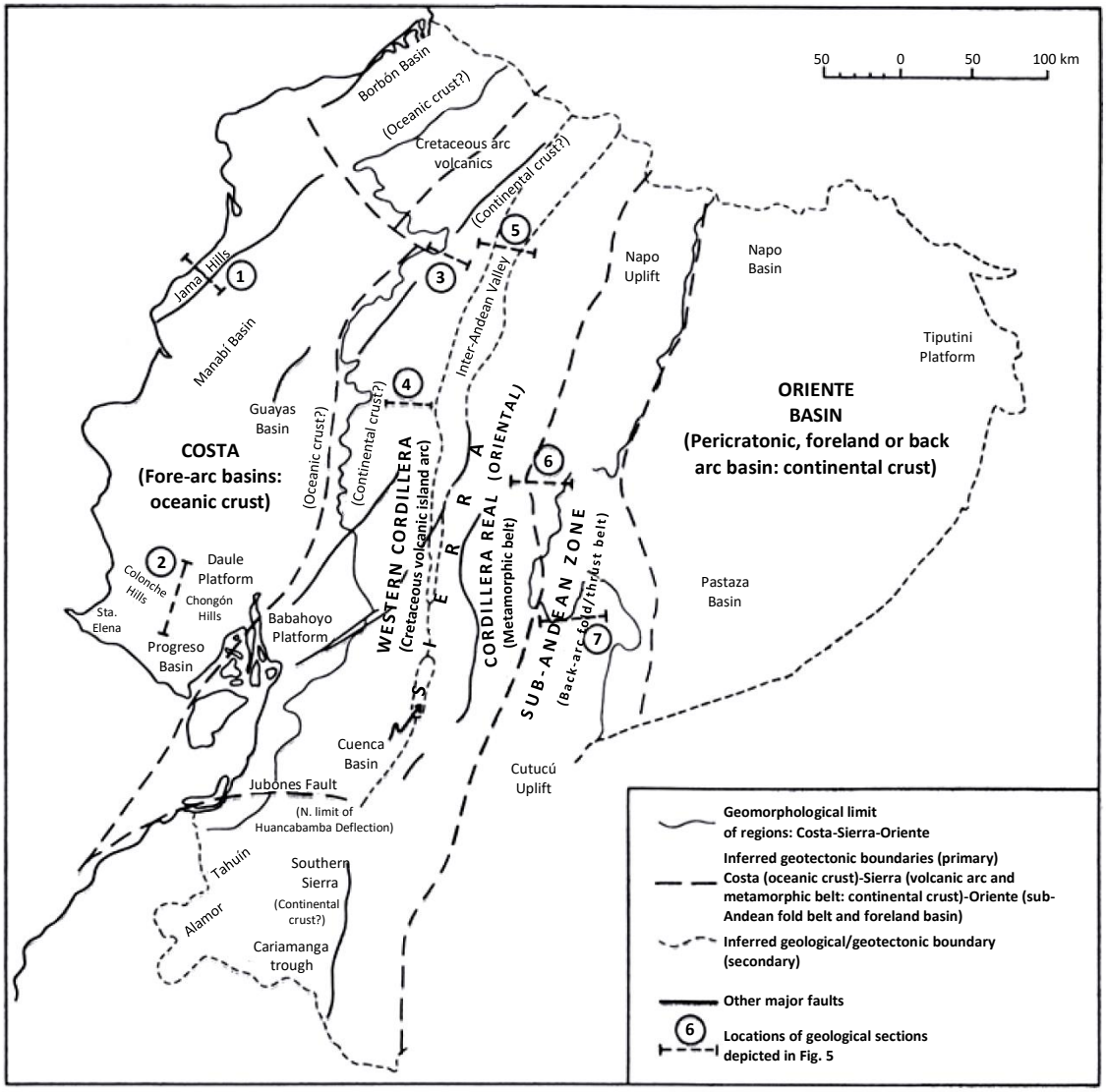


Fig 2. The geomorphological and geological framework of Ecuador

The core of the Cordillera Real, however, is probably composed of Paleozoic (and older?) metamorphic rocks. Mortimer (1980a) mapped the Llanganates Group (schists and gneisses) as being of (undifferentiated) Paleozoic age, following Kennerley's (1971) demonstration of two phases of folding in the central Cordillera Real. Pre-Mesozoic, possibly Lower Paleozoic, metamorphic rocks, mainly schists of the Zamora Group, with a northerly or northeasterly strike are exposed in the southern Cordillera Real (Kennerley, 1973; Kennerley, 1980). East of Cuenca, the late Mesozoic metamorphics (Paute Group) can be distinguished from the older (Paleozoic?) core (Zamora Group) on the basis of tectonic style and metamorphic grade. Although the contact has not been mapped, it may be (thrust?) faulted (Baldock and Longo, 1982). Northward the metamorphic rocks (Llanganates and Ambuquí Groups) of the Cordillera Real, described by Herbert (1977), may link with those that have been considered to be Paleozoic and Precambrian in southernmost Colombia (INGEOMINAS, 1976), although again some may be Cretaceous (Feininger, 1974). Recent attempts to resolve the metamorphic history by Rb/Sr age determinations along sections across the Cordillera Real have produced confusing results.

Along much of its length the Cordillera Real is capped by Neogene andesitic lavas and acid pyroclastics and ignimbrites, usually directly overlying metamorphic rocks. It is bounded to the west by the depressions or faulted grabens of the inter-Andean valley (Colombian border to Riobamba), Cuenca Basin, and Cariamanga-Gonzanamá Trough, filled with Cretaceous shales/volcaniclastics (Alamor Group), and flysch-facies shales and turbidites (Yunguilla Formation, see p. 8-9), both partially overlain by Mio-Pliocene freshwater sedimentary and volcaniclastic deposits.

2. Western Cordillera

The Western Cordillera is mainly composed of an 8 km thick sequence of Cretaceous to Paleogene or Eocene andesite and basaltic andesite lavas and volcaniclastics, now distinguished as the Macuchi Formation, (Henderson, 1979, 1981). The lavas have spillitic affinities and exhibit pillow structures. Isotopic studies show that the parental calc-alkali magma was mantle derived (Francis *et al.,* 1977). Intercalated marine (turbiditic) sediments are present (Chontal Member, where differentiated) especially in northern Ecuador (Guzmán, 1980). The succession represents a (eugeosynclinal) volcanic island arc assemblage, mainly of relatively deep-water origin (Henderson, 1979). It is presumed that the sequence is now floored at depth by continental lithosphere (metamorphic rocks) or transitional crust, but this is nowhere exposed, except perhaps in isolated schistose outcrops (Punta Piedra Formation) of dubious origin in the Guayaquil region (Fig. 1). In the extreme north there is gravity evidence of a change to an ensimatic arc (Feininger, 1977). The Macuchi Formation extends with little lithological change from immediately north of the Jubones Fault in southern Ecuador (Zúñiga, 1980) to the border with Colombia and beyond, where it is known as the Diabase Group. Recent mapping indicates that there is no major lithological change across the Pallatanga (Puná-Pallatanga-Riobamba) Fault Zone (Fig. 4) (Guevara, 1979), which has previously been taken as the tectonic contact between the Macuchi and Celica (Feininger and Bristow, 1980; Hall and Calle, 1982).

However, the Macuchi is not a simple, continuous, north-northeasterly trending volcanic arc assemblage: the bulk of the formation is (Upper) Cretaceous, and, in places, it is overlain by fossiliferous Maastrichtian sediments of the Yunguilla Formation (see p. 8-9) and by volcaniclastics of the Silante Formation, which may perhaps be pre-Maastrichtian (Henderson, 1979). In other localities Macuchi-type volcaniclastics contain Eocene faunas associated with the local development of limestones (Echeverría, 1977; Henderson, 1979; Longo, 1980). The volcanic arc sequence, therefore, was evidently formed during the Upper Cretaceous-Eocene period — perhaps in two separate phases of activity. It may have subsequently (in the late Eocene or early Oligocene) been emplaced tectonically (Feininger and Bristow, 1980), probably in a series of northeasterly trending "slices" bounded by discontinuous, partly en echelon faults, which branch off from the main Guayaquil-Dolores suture (Fig. 4). Such faults may have brought volcanosedimentary successions of similar lithology but differing age into juxtaposition in adjacent blocks (Fig. 4 and Fig. 5; sections 3, 4, and 5) (Baldock and Longo, 1982), but more detailed work is needed to verify this interpretation. The overall, slightly arcuate, northerly trend suggests that the older, stabilized metamorphic belt of the proto-Cordillera Real played an important role in the final configuration of the volcanic arc.

In southern Ecuador Cretaceous volcanism appears to have mainly subaerial, with deposition partly on a positive Paleozoic microcratonic block — the transverse Amotape-Tahuín Ridge (Kennerley, 1980) — and partly in the marine Cariamanga Trough (part of the NW Perú Basin, Cobbing *et al.,* 1981). The volcanic rocks of the Celica Formation, which show much less evidence of submarine eruption, are limited to the area south of the Jubones Fault system (Figs. 2 and 4), which is a major structure (possibly also a branch of the Guayaquil-Dolores Suture). The Jubones Fault appears to form the northern limit of the Huancabamba deflection, and delimit the northern margin of the Precambrian to Paleozoic Tahuín metamorphic block, composed of the Piedras and Tahuín Groups (Feininger, 1978; Zúñiga, 1980). The Cretaceous volcanic arc is associated with the marine sediments and volcaniclastics of the Alamor Group (Cazaderos and Zapotillo-Ciano Formations) in the extreme SW of Ecuador (Kennerley, 1973). It apparently continues southward and may once have been linked to the andesitic Casma Arc in Perú (Hall and Calle, 1982), which also exhibits both submarine and subaerial facies (Cobbing *et al.,* 1981). The Casma Group forms the envelope of the great coastal batholith of Perú (Cobbing *et al.,* 1981; and in Chapter 6 of this volume), which continues at least into southern Ecuador where it is present as the middle Cretaceous Tangula Batholith and other related intrusive bodies (Fig. 3; Kennerley, 1973, 1980). Paleocene volcanics (Sacapalca Formation) in the Cariamanga Graben of southern Ecuador also appear to correlate southward with the Older Calipuy volcanic cycle of northern Perú. The overall geographical continuity of Cretaceous-Paleocene volcanism from Perú to Colombia suggests that the Ecuadorian section of the arc also built up as a result of subduction over a more or less continuous earlier trench system (from Perú to Colombia) located a little (50-100 km) to the west of the present position of the Cretaceous arc volcanics in the Western Cordillera. A more complex interpretation, involving three successive subduction zones and the creation and destruction of a hypothetical oceanic plate, has been proposed by Feininger and Bristow (1980).

In northern Ecuador the Macuchi volcanics are overlain by red to greenish- grey volcaniclastic rocks (and minor lavas) of the Silante Formation, which is some 5400 m thick. Henderson (1979) reported (way-up) evidence that the Silante underlies Maastrichtian shales of the Yunguilla Formation (Fig. 5; section 3) and is therefore Upper Cretaceous, although it was previously thought to overlie the Yunguilla and to be of Paleocene age (Savoyat *et al.,* 1970; Faucher and Savoyat, 1973; Bristow and Hoffstetter, 1977).

The Yunguilla Formation consists of turbiditic flyschlike shales, siltstones, and volcaniclastics, with rare limestones. A conglomeratic member (Cayo Rumi) near the top of the formation suggests a shallower-water environment and rapid erosion of proto-Cordillera metamorphic rocks to the east. The Yunguilla Formation is Maastrichtian in age (Sigal, 1968; Savoyat *et al.,* 1970), but may include some Paleogene sediments. Although Henderson (1979) viewed the Yunguilla (as well as the Macuchi) as a strongly diachronous formation, volcaniclastic and carbonate rocks with an Eocene fauna, previously assigned to the Yunguilla, are perhaps better denominated separately (Feininger and Bristow, 1980). Although not yet lithostratigraphically defined, these have been termed the Unacota Formation (see Longo, 1980); such Eocene sediments have so far only been mapped in very restricted areas (Baldock and Longo, 1982). Further study and remapping of the flyschlike Yunguilla of the Sierra is required to clarify these relationships.

Numerous plutonic bodies intrude the Upper Cretaceous-Eocene sequence of the Western Cordillera. Most of the intrusions north of the Jubones Fault are probably of Neogene age and are relatively small, except the Apuela Batholith in northern Ecuador (Fig. 3), which has contact metamorphosed limestones of presumed Eocene age (Guzmán, 1980). The post-Eocene plutons of the Western Cordillera of Ecuador are quite unlike the composite coastal batholith of Perú (Cobbing and Pitcher, 1972; Cobbing *et al.,* 1981; and Cobbing, Chapter 6 of this volume).

Widespread Oligo-Miocene volcanic deposits (andesitic to rhyolitic lavas and pyroclastics) of the Saraguro Group (Alausí, Saraguro, Loma Blanca, Chinchillo Formations) cover the southern sector of the Ecuadorian Andes. Some of the pyroclastics were deposited in the freshwater sedimentary basins developing within the proto-Cordillera (Kennerley, 1980). In the Cuenca Basin (Liddle and Palmer, 1941; Bristow, 1973) shales and arenaceous sediments of the Biblián Formation and Azogues and Ayancay Groups include subsidiary volcaniclastics; coals were developed in the Mangán Formation of the Ayancay Group (UNDP, 1969). Further south, similar (mainly lacustrine) sequences (Nabón Formation and Quillollaco Group) occur within the Nabón, Loja, and Malacatus basins (Kennerley, 1973; Bristow, 1976b). In northern Ecuador conglomerates and tuffaceous sediments (Chota Group) within the Chota Basin (Hall *et al.,* in press) may be of a similar age.

Late Neogene and Quaternary volcanic deposits (for example, the andesitic lavas and pyroclastics of the Pisayambo Formation in the central Sierra, and the widespread Pleistocene rhyolites and ignimbrites of the Tarqui Formation in the south) cover much of the Cordillera. The numerous volcanic centers and major stratovolcanoes of Pliocene-Recent age that dominate the Ecuadorian Andes are confined to the central and northern parts of the country, but continue into southern Colombia (Hall, 1977). Plio-Quaternary pyroclastic and ash deposits (Cangagua Formation) infill the down-faulted inter-Andean valley (Fig. 5; section 5), in places to a depth of more than 1000 m.

C. Geology of the Costa

The Costa represents a late Cretaceous-Tertiary fore-arc basin (or series of basins, formed in the arc-trench gap) underlain by Cretaceous basaltic volcanics of the Piñón Formation, which is exposed in the Chongón-Colonche and lama-Mache Hills (Fig. 2). The term "Piñón" (Tschopp, 1948) has previously had a varied usage (see Bristow and Hoffstetter, 1977), but it is now more strictly applied to the sequence of basalts, basaltic pyroclastics, and minor associated sediments and volcaniclastics in the Ecuadorian coastal region (Feininger and Bristow, 1980; Baldock and Longo, 1982). The Piñón basement of the Costa is tilted and block-faulted (Fig. 5; sections 1 and 2), but not substantially metamorphosed. Gravity data (Feininger, 1977) indicate that the Piñón is characterized by extremely strong positive Bouguer anomalies and cannot be underlain by felsic continental crust. Chemical analyses show that the basalts are tholeiitic (Goossens and Rose, 1973; Goossens et al., 1977); they could be of true oceanic (Feininger and Bristow, 1980) or of primitive island arc origin (Henderson, 1979). The Piñón Basalt, therefore, must either represent ocean floor material or directly overlie Mesozoic oceanic crust, accreted into the continental South American plate.

In much of the Costa the Piñón is covered by a thick Upper Cretaceous and Tertiary sedimentary succession that was principally deposited in several troughs within the NNE-trending Bolívar Geosyncline (Nygren, 1950) or in the fore-arc basin extending from NW Perú to Panama: the Progreso Basin to the south of the Chongón-Colonche Hills; the elongate Manabí Basin of central coastal Ecuador, divided into southern and northern depocenters (Fig. 4); and the Esmeraldas-Borbón Basin in the north, which continues as the Tumaco Basin of southwestern Colombia. The Piñón Basalts are overlain by Upper Cretaceous (Senonian-Maastrichtian) volcaniclastic and sedimentary rocks (silicified tuffs and shales, with sandstones and agglomerates towards the base) of the Cayo Formation (Bristow, 1976a; Bristow and Hoffstetter, 1977), which correlates directly with the Macuchi Island Arc Volcanics of the Sierra (Feininger and Bristow, 1980), but were deposited to the west of the Guayaquil-Dolores Suture in the ensimatic forearc basin.

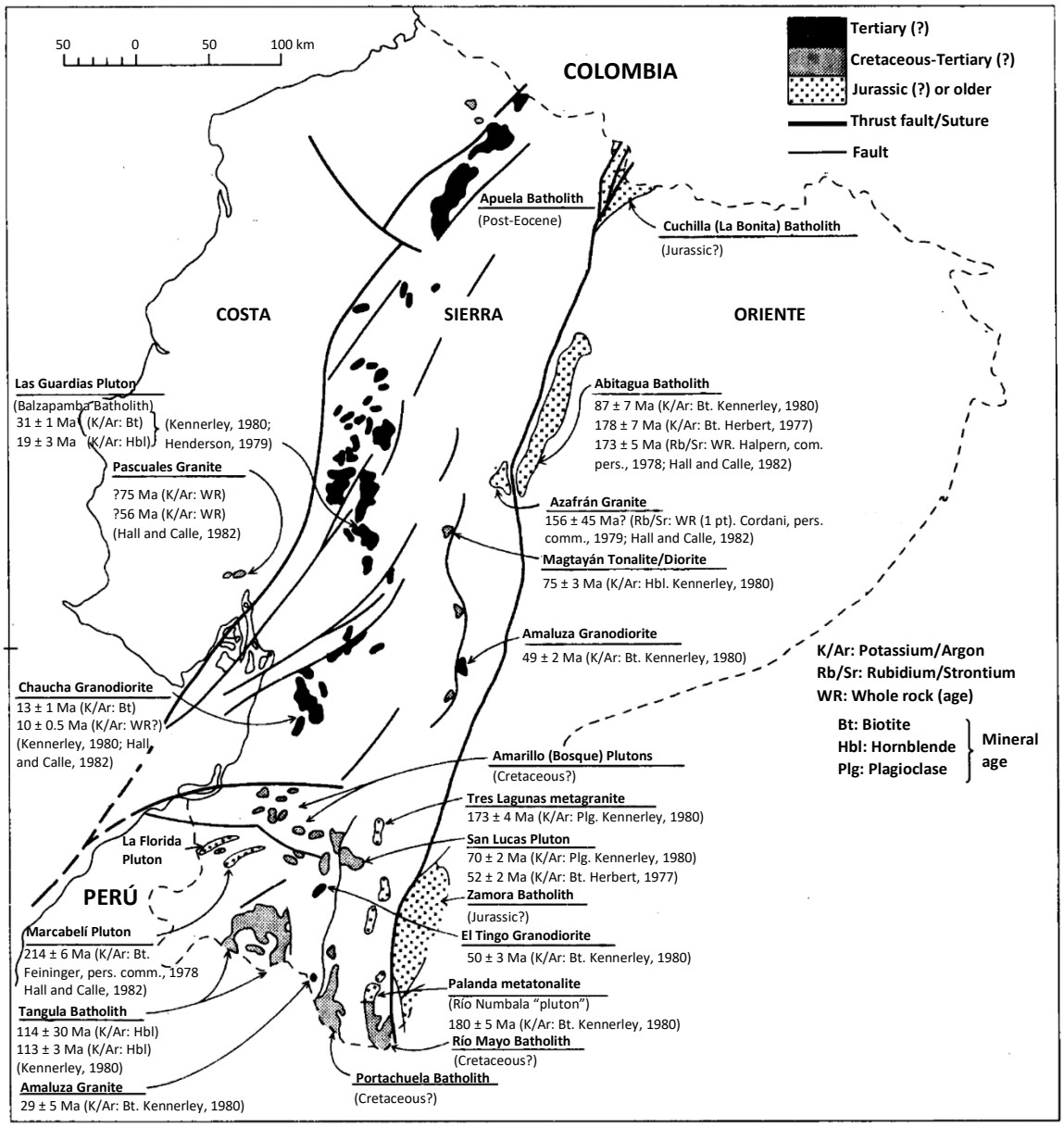


Fig 3. The distribution and inferred ages of plutonic rocks in Ecuador

Tertiary sedimentation in the Costa commenced in the middle Eocene with the San Eduardo (and Ostiones) Limestones (Mills, 1968), which are considered to be of redeposited, turbiditic origin (Feininger and Bristow, 1980; Evans and Whittaker, 1981). After a period of little or no deposition in the Oligocene, sedimentation resumed in the late Oligocene-early Miocene, resulting in sequences up to 9 km thick in the Progreso Basin of southern Ecuador (Colman, 1966, 1970) and up to 4 km thick (Manabí and Esmeraldas-Borbón basins; see below) in central and northern Ecuador (Canfield, 1966; Faucher *et al.*, 1971; Evans and Whittaker, 1981).

Submarine slumping on a gigantic scale into the Progreso Basin in the late Eocene led to the emplacement of the allochthonous Paleocene-Eocene Santa Elena Olistostromic Complex in the Santa Elena Peninsula (Azad, 1964; Colman, 1970). A condensed description of the complex, and one interpretation of its origin and derivation, has been given by Feininger and Bristow (1980). In the Manabí and Esmeraldas-Borbón regions, more normal Eocene sedimentation deposited the shale, sandstone, and mudstone sequences of the San Mateo-Punta Blanca and Zapallo Formations (Mills, 1967; Evans and Whittaker, 1981). In the Borbón Basin the Zapallo is overlain (apparently conformably) by Oligocene mudstones and sandstones of the Pambil Formation (Evans and Whittaker, 1981).

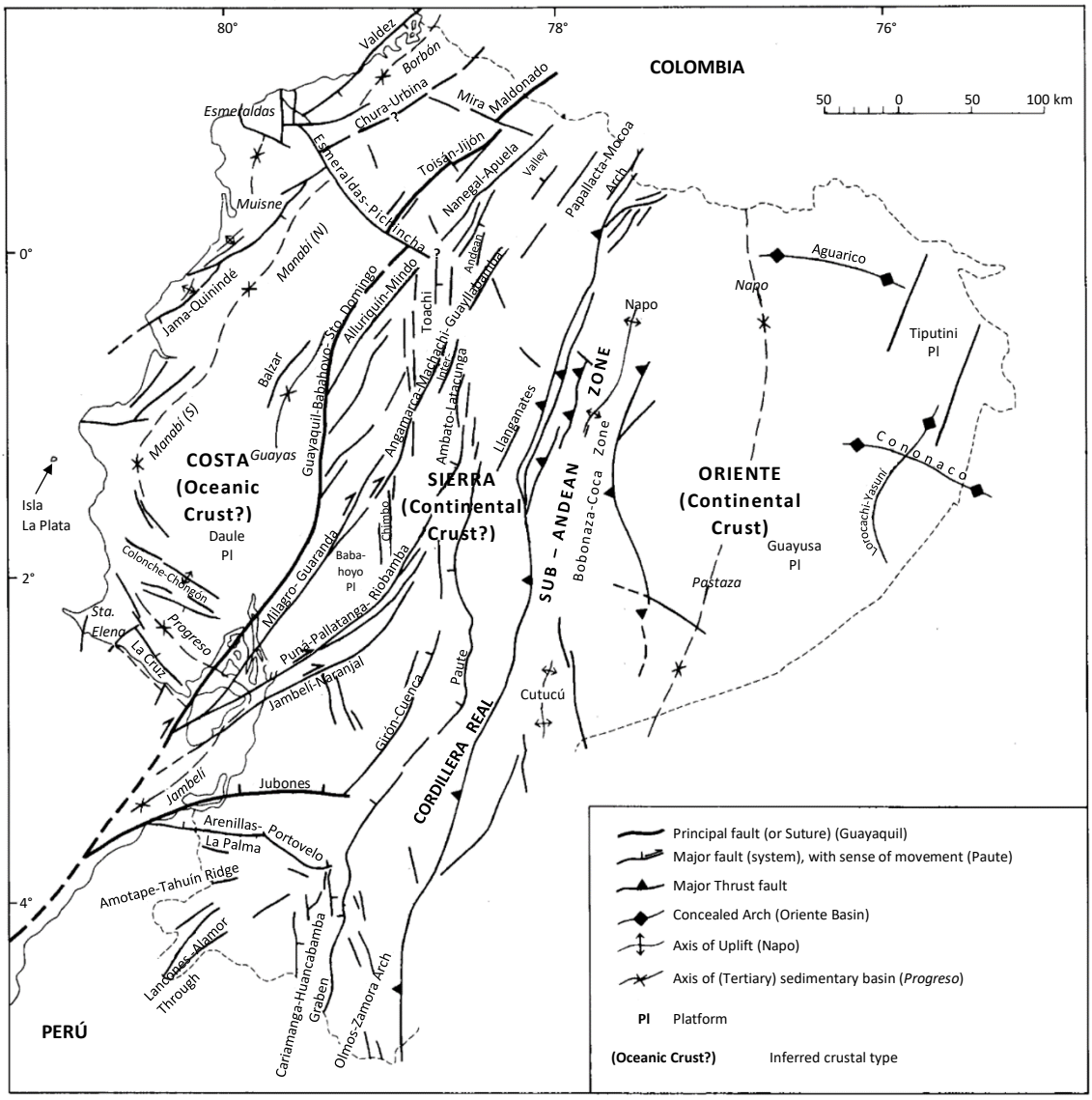


Fig 4. The main structural features of Ecuador

Following the postulated widespread middle-Oligocene unconformity, late Oligocene and Miocene sediments of the Tosagua Formation were deposited in the Progreso and Manabí basins: the lowest conglomeratic/arenaceous member (Zapotal) is restricted to the region south of the Chongón-Colonche Hills (Bristow, 1975). The Dos Bocas Member (siltstones and mudstones) spans the Oligocene-Miocene boundary and is overlain by the Villingota Member (Bristow and Hoffstetter, 1977). The equivalent Lower Miocene Viche Formation (mudstones with thin siltstones) was deposited in the Esmeraldas-Borbón Basin. The middle to late Miocene Daule Group (arenaceous and argillaceous sediments of the Angostura, Onzole, and Borbón Formations) occurs in both the Esmeraldas-Borbón and Manabí regions (Bristow, 1976c). South of the Chongón-Colonche Ridge, a thick Miocene sequence of sands, silts, and clays (Progreso Formation) was deposited in the subsiding Progreso-Jambelí Basin, which was formed by a pull-apart mechanism, and is still active (see Shepherd and Moberly, 1981). Sedimentation continued during the Plio-Quaternary in parts of the present coastal region (Puná, Tablazo, and Cachabí Formations). In the central and southern Costa, Neogene uplift of the marginal hills, which represents the rise of the mid-slope high (Evans and Whittaker, 1981) caused an eastward migration of the axis of the sedimentary trough: at least 1500 m of piedmont, laharitic, and fluviatile material (Balzar, San Tadeo, and Pichilingue Formations) was deposited closer to the uplifted Andes in the Guayas Basin-Gulf of Guayaquil.

In northern Ecuador the Tertiary sequence on the southeast of the Borbón Basin apparently overlies island arc andesites (Macuchi); it is not known whether the Andean foothills in this region partly comprise Piñón, but positive gravity anomalies (Feininger, 1977) suggest that oceanic crustal material may underlie the Macuchi in that area, which would be typical for a residual fore-arc basin developed "on oceanic or transitional crust trapped between the arc massif and the subduction zone" (Dickinson and Sealy, 1979; see also Evans and Whittaker, 1981). In the central Costa (Guayas Basin) the thick Plio-Quaternary piedmont deposits conceal the supposed more abrupt change from the felsic lithosphere beneath the Western Cordillera, to the oceanic crustal environment of the Costa (Figs. 2 and 4; see also the gravity data in Feininger, 1977).

Apart from the very small Paleocene-Eocene Pascuales Granite near Guayaquil (Fig. 3), no plutonic rocks are known in coastal Ecuador — which highlights the difference between this sector of the eastern Pacific margin, compared with the Perú region to the south.

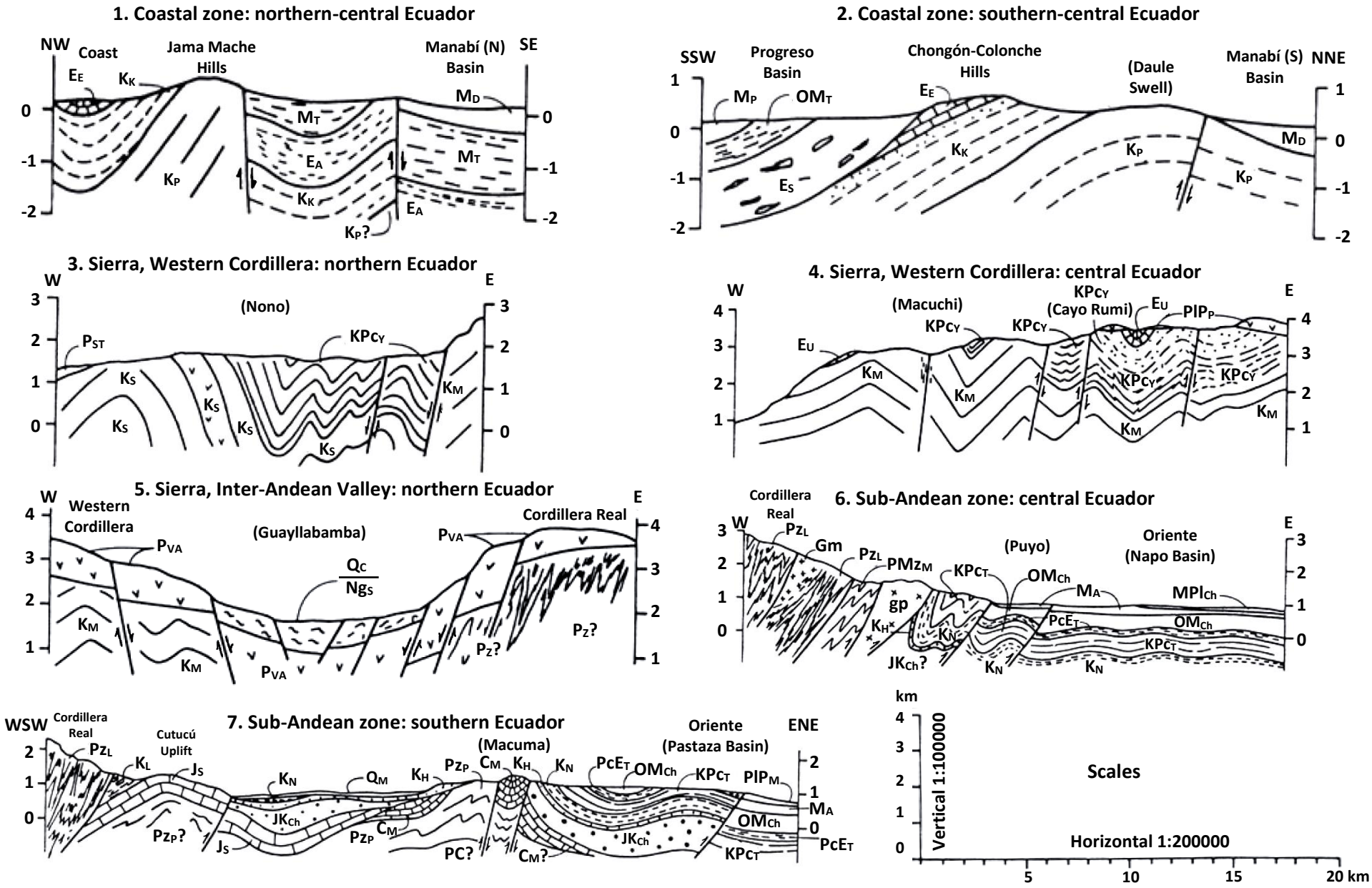


Fig. 5 Diagrammatic sections to illustrate the differences in structural styles. See Fig. 1 for stratigraphic symbols and Fig. 2 for locations.

D. Geology of the Offshore and Galápagos Islands

1. *Continental Shelf and Trench*

Part of the continental shelf between the present coastline of Ecuador and the offshore trench has been investigated in outline (Aldrich, 1977; Lonsdale, 1978; Shepherd and Moberly, 1981). Piñón Basalts crop out on Isla La Plata (Sheppard, 1927) off the coast of Manabí (Fig. 4). Geophysical and borehole evidence (unpublished data; Shepherd and Moberly, 1981) suggests that thick Upper Cretaceous and Cenozoic sequences, similar to those onshore, were deposited in various (partly fault-bounded) troughs within forearc and trench-slope basins. In the Gulf of Guayaquil, the NE-SW-trending sector of the Progreso Basin continues to the south as the Jambelí-Tumbes Basin, in which more than 10000 m of Tertiary sediments have been deposited (Olsson, 1932). The Jambelí (Gulf of Guayaquil) Basin (see Fig. 4) obscures the important Guayaquil-Babahoyo-Santo Domingo Suture, which was probably a major transform fault (also called the Guayaquil Romeral Fault; Fig. 6) separating the continental crust (South American plate) to the east from the old (Mesozoic) oceanic crust (proto-Nazca plate) (Feininger and Bristow, 1980). This isolated and partially preserved piece of old oceanic crust, accreted to the continental plate, is limited to the west by the present trench system. Structurally the boundary may be a zone of imbricate thrust faulting (Lonsdale, 1978; Lonsdale and Klitgord, 1978) on the inner slope of the trench, which reflects the junction between the inactive Mesozoic oceanic crust and the spreading/subducting Neogene oceanic crust of the Nazca plate (Fig. 6) (Shepherd and Moberly, 1981).

2. Pacific Margin

The margin of the Pacific Basin west of the Ecuador Trench is composed of Miocene and younger oceanic lithosphere (Nazca plate), formed at the Cocos-Nazca (or Galápagos) Rift Zone, and overlain by pelagic sediments. To the west of the Gulf of Guayaquil and southeast of the Grijalva Fracture Zone, the northernmost part of the Chile-Perú Trench is subducting Upper Eocene and Oligocene crust (Fig. 6) generated at the older Galápagos Rise spreading system (Menard *et al.*, 1964; Lonsdale, 1978).

West of the trench, off central Ecuador, lies the submarine Carnegie Ridge, which is interpreted as an aseismic volcanic feature formed either as the Nazca plate moved eastward over the Galápagos hot spot (Hey *et al.*, 1977) or by volcanic thickening of the oceanic crust during slow spreading from the E-W Galápagos Rift Zone. The relatively shallow nature of much of the Ecuador Trench results from subduction of this thickened oceanic lithosphere at the eastern end of the ridge (Lonsdale, 1978). Southward, between the Carnegie Ridge and the Grijalva Fracture Zone, lies an area of older, smoother-surfaced and thinner crust, presumably formed before development of the hot spot or during more rapid spreading during the middle Miocene (Macdonald and Mudie, 1974). North of the Carnegie Ridge (off northern Ecuador and southern Colombia) there is a complex zone of late Miocene-Pliocene oceanic crust that was generated by spreading from the reactivated E-W-trending spreading axis and displaced along the Panama Fracture Zone and other transform faults, in the southern sector of the Panama Basin (Fig. 6) (Lonsdale and Klitgord, 1978).

The Carnegie Ridge continues (and gets younger) westward, joining the Cocos Ridge some 1000 km west of the mainland to form the submarine Galápagos Platform (Holden and Dietz, 1972) on which the Galápagos Islands have been built up to above sea level by Plio-Quaternary volcanism over a zone of crustal weakness (fossil transform fault) or a hot spot (Rea and Malfait, 1974; Anderson *et al.*, 1975).

3. Galápagos Islands

The islands of the Galápagos Archipelago thus occur on the northern edge of the Nazca plate, at the intersection of the Carnegie and Cocos submarine ridges (Cox, 1975), roughly midway between the South American coast and the East Pacific Rise. The Galápagos comprise some 14 main islands and numerous islets, all composed principally of Plio-Quaternary volcanic rocks, (McBirney and Williams, 1969; Nordlie, 1973) largely derived from the 15 major volcanoes that rise some 4500 m from the seafloor or Galápagos Platform. The islands have been classified into five groups (Hall, 1977) on the basis of their age and petrology, mainly comprising typical shield volcanoes (Banfield *et al.*, 1956; Nordlie, 1973) or their partially dissected remnants, and composed of olivine-poor tholeiitic basalt or of alkaline olivine-basalts, although a distinct group comprise uplifted blocks of older submarine basalts.

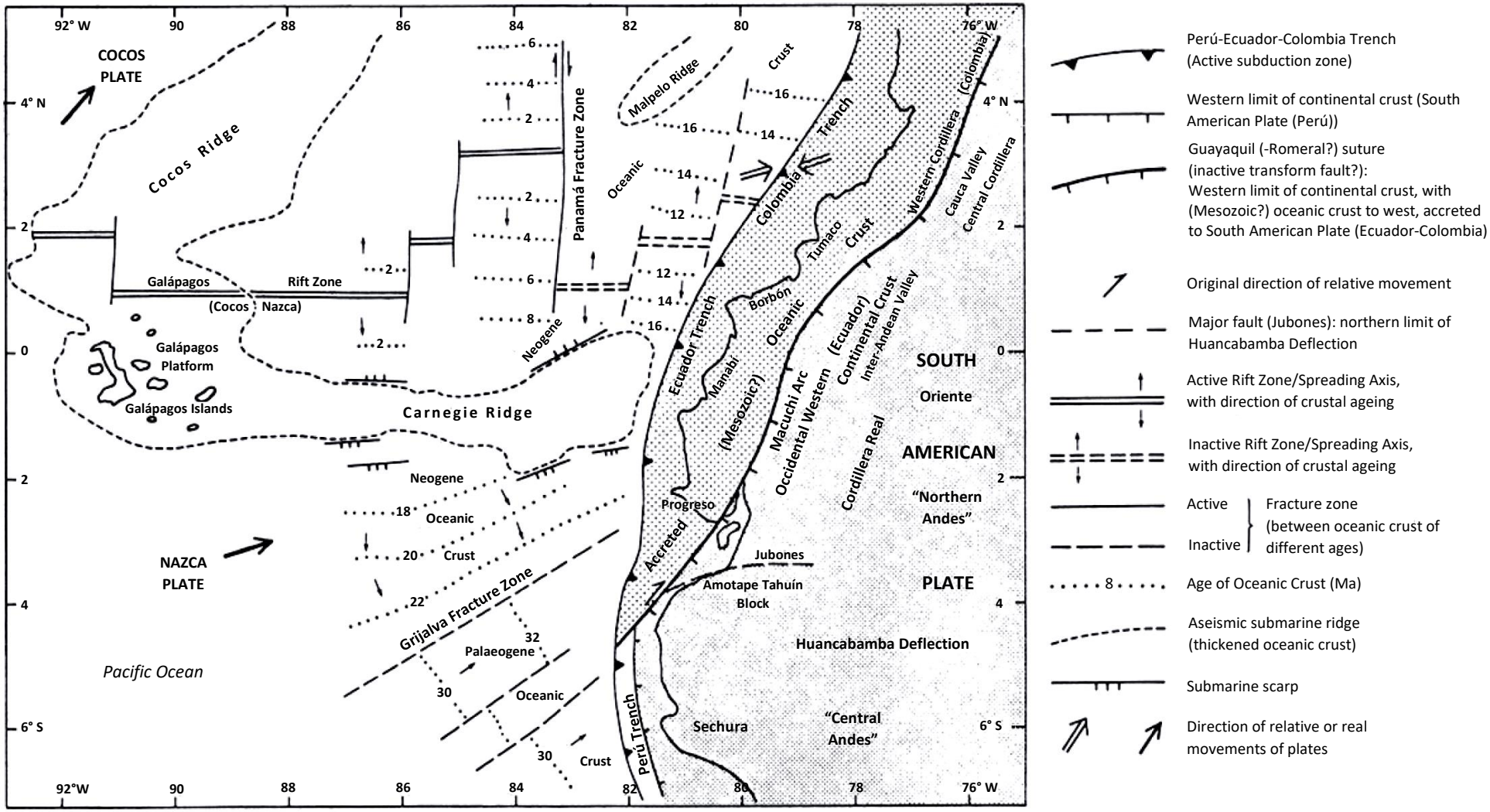


Fig. 6 Plate tectonic framework of Ecuador (mainland, ocean floor, and Galápagos Islands)

III. CORRELATION AND GEOLOGICAL HISTORY

Having reviewed the geological framework of the separate regions of Ecuador, an attempt can now be made briefly to correlate these distinct environments and present a tentative history of this sector of the Pacific Margin.

A. Precambrian and Paleozoic

Archean cratonic rocks of the Guyana Craton are nowhere exposed in Ecuador, but underlie the sedimentary epiplatform cover in the Oriente Basin. Precambrian rocks (Piedras Group) crop out in a small area of the Tahuín block, perhaps representing a relic of greenstone terrain.

Metamorphic rocks (schists and phyllites) of the Excelsior Group in the Olmos Arch region in the (western) Cordillera of northern Perú, which forms a direct continuation of the Cordillera Real of southern Ecuador, are clearly overlain by fossiliferous Triassic, and probably also Devonian, sediments (Cobbing *et al.,* 1981), while further south in central Perú the Excelsior Schists have been shown to the pre-Ordovician (Megard *et al.,* 1971). Hence it is supposed that the equivalent metamorphic rocks of the Cordillera Real, at least those of the (southernmost) Zamora Group (Kennerley, 1973) perhaps also those of the Llanganates (Mortimer, 1980a) and Ambuquí Groups, may also be substantially of Lower Paleozoic age. Metamorphic rocks of probable Paleozoic age (Capiro Formation of the Tahuín Group) are also exposed in the Tahuín block, but their relationship with the Cordillera Real is uncertain.

Upper Paleozoic sediments (Pumbuiza and Macuma Formations) were deposited in the Oriente on the western margin of the Guyana Craton; unmetamorphosed remnants are only exposed in the Cutucú Uplift and perhaps along the flank of the sub-Andean zone, but may occur beneath the Mesozoic cover in the Oriente. Coeval, but perhaps deeper-water, sediments (e.g., Margajitas Formation) further west may have subsequently been deformed together with the Lower Paleozoic(?) core of the Cordillera Real.

B. Mesozoic: Pre-Cretaceous

Confused (unpublished) radiometric data for rocks collected from the central (Baños) and northern (Papallacta) Cordillera Real could suggest a period of Triassic metamorphism. Between the supposed proto-Cordillera Real positive axis and the margin of the craton, Mesozoic deposition is first recorded in the Oriente Basin by the dominantly continental/red-bed sediments of Upper Jurassic age (Chapiza Formation). In Ecuador it was accompanied, but chiefly followed, by widespread Jurassic-Cretaceous igneous activity (Misahuallí volcanics and Guacamayos subvolcanics). Original intrusion of the three large batholiths along the edge of the Cordillera Real may have been earlier (middle Jurassic) or contemporaneous (Hall and Calle, 1982).

C. Mesozoic: Cretaceous

The oldest rocks exposed in the Costa and Western Cordillera (excepting the metamorphics of the Tahuín block) are Cretaceous (Goossens and Rose, 1973; Bristow and Hoffstetter, 1977). Consequently, virtually nothing is known of the pre-Cretaceous geological environment of Ecuador west of the Cordillera Real. The occurrence of ultrabasic rocks and high-pressure metamorphics (Feininger, 1980), perhaps of Cretaceous age, to the north of, or thrust into, the Tahuín block suggest that the Jubones and Arenillas- La Palma faults (Fig. 4) might be surficial expressions of Cretaceous or earlier subduction. The earliest Piñón Basalts of the Costa are probably of later Lower Cretaceous and early Upper Cretaceous age (Bristow and Hoffstetter, 1977), and probably represent an upper layer of Cretaceous ocean floor material (Feininger and Bristow, 1980; Hall and Calle, 1982).

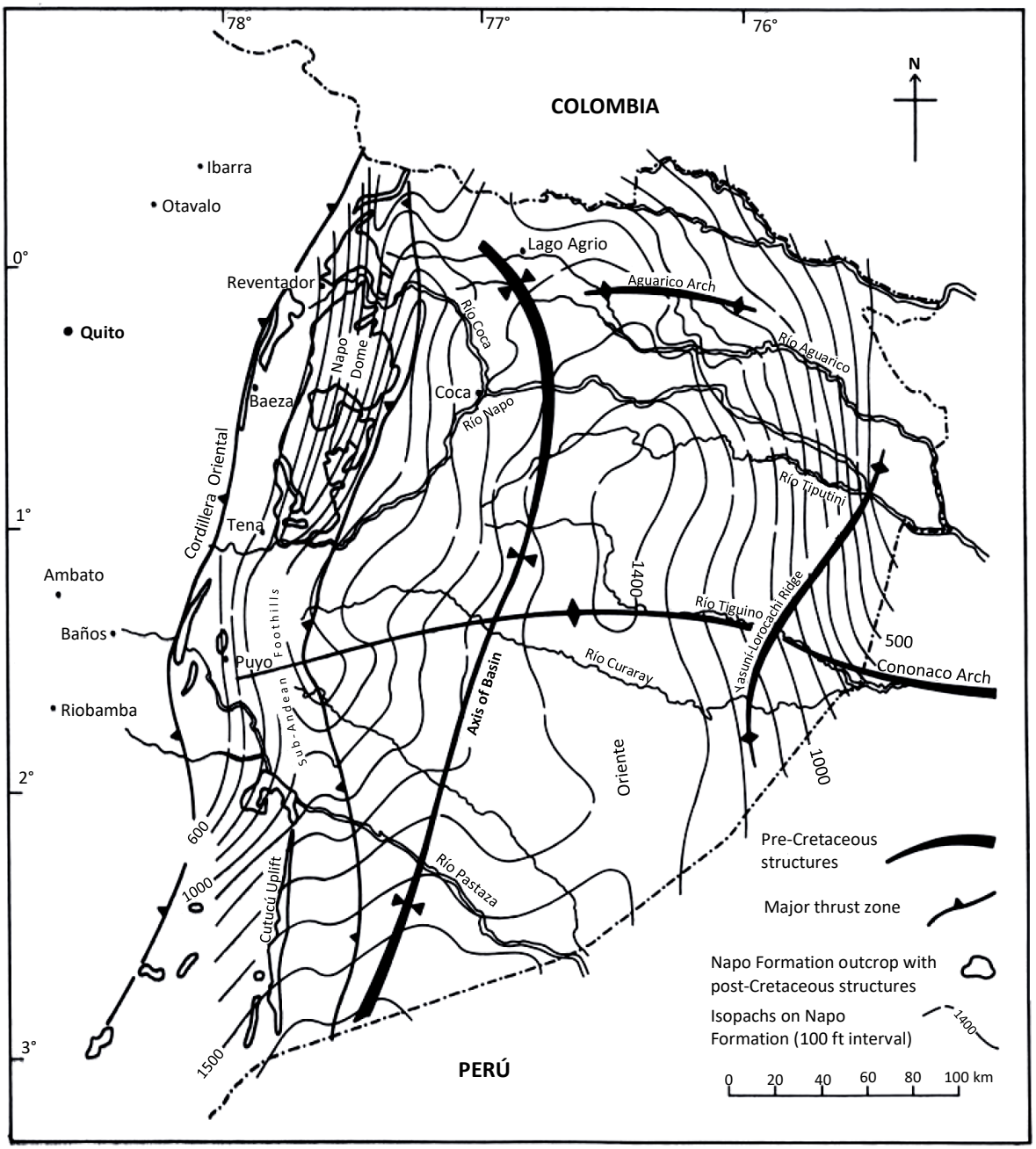


Fig. 7 Napo Formation thickness and outcrop areas, showing pre-Cretaceous structural elements and post-Cretaceous thrust zones. Reproduced from Wilkinson (1982)

Aptian and younger Cretaceous rocks are considered to have been deposited in a paired geosynclinal couple, separated by the positive Olmos Arch-proto-Cordillera Real axis. The miogeosynclinal, foreland (or backarc) basin of the Oriente received a mainly nonvolcanic clastic/carbonate sequence: the Hollín and Napo Formations (Fig. 7; reproduced from Wilkinson, 1982), which span the Aptian to mid-Maastrichtian period (Wilkinson, 1982; Whittaker and Hodgkinson, 1979). Compelling evidence, summarized by Wilkinson (1982), does indicate that even during the early Upper Cretaceous the Oriente Basin was delimited on the west by the positive, although not necessarily emergent, proto-Cordilleran axis, rather than by deep open water (Fig. 8; reproduced from Wilkinson, 1982; see also Fig. 9 reproduced from Kennerley, 1980; Feininger, 1975; and Feininger and Bristow, 1980, for a previous view).

The volcanic arc began to develop in the more rapidly subsiding (eugeosynclinal) basin to the west of the Cordillera Real positive axis in the late Lower Cretaceous or very early Upper Cretaceous. The earliest products are probably the subaerial volcanics (Celica Formation) overlying part of the Tahuín block, and their marine equivalents deposited as a volcanosedimentary succession (the Aptian to Campanian Alamor Group), in the Lancones-Alamor Trough (part of the northwest Peruvian Basin) of southwesternmost Ecuador (Fig. 9; from Kennerley, 1980). These volcanics and pyroclastics indicate a southward link with the Casma Arc in Perú, which is dominantly Albian (to Cenomanian) in age, mainly marine, but partly subaerial, and also very sharply delineated to the east (Cobbing *et al.*, 1981).

Northward, along the main Western Cordillera, the island arc andesites and volcaniclastics of the Macuchi Formation are of undoubted Upper Cretaceous (and Paleogene) age at their top; their lower age is unknown, although it may be as early as Cenomanian (Henderson, 1979, Fig. 4), perhaps even Albian. Although obviously somewhat diachronous over such a distance, the possible correlation of the (lower?) Macuchi with the Celica, and hence with the Casma Arc of Perú, does suggest a continuity of Cretaceous arc volcanism from Perú to Colombia, all related to one eastward-dipping subduction zone (but see Feininger and Bristow, 1980, for a different interpretation). Sediments associated with the Macuchi Volcanics (Chontal Member) are widespread in northern Ecuador: they apparently continue northward (as the Upper Cretaceous Espinal Formation of the Dagua Group) into Colombia (Barrero, 1979). The Macuchi Volcanics now probably rest mainly on sialic basement: highly negative gravity anomalies are characteristic of most of the Western Cordillera of Ecuador. However, north of the Esmeraldas- Pichincha Fault (Fig. 4) the Macuchi arc may rest directly on oceanic crust, giving rise to positive gravity values that continue northward into the Western Cordillera of Colombia (Feininger, 1977). In the Costa, a thick volcano-sedimentary sequence (Cayo Formation) that directly overlies the Piñón Basalts, was deposited in a developing, ensimatic, fore-arc basin (Fig. 9) in the arc-trench gap and is the lateral equivalent of the Macuchi Formation (Feininger and Bristow, 1980).

By the end of the Cretaceous and in early Tertiary time, much of proto-Cordillera Real was emergent and undergoing erosion to provide the source of some of the clastic material deposited both in the Oriente Basin (Tena Formation) and in the (discontinuous?) interarc basins of the Sierra (flysch-facies Yunguilla Shales and Cayo Rumi Conglomerates (Fig. 10; reproduced from Kennerley, 1980)).

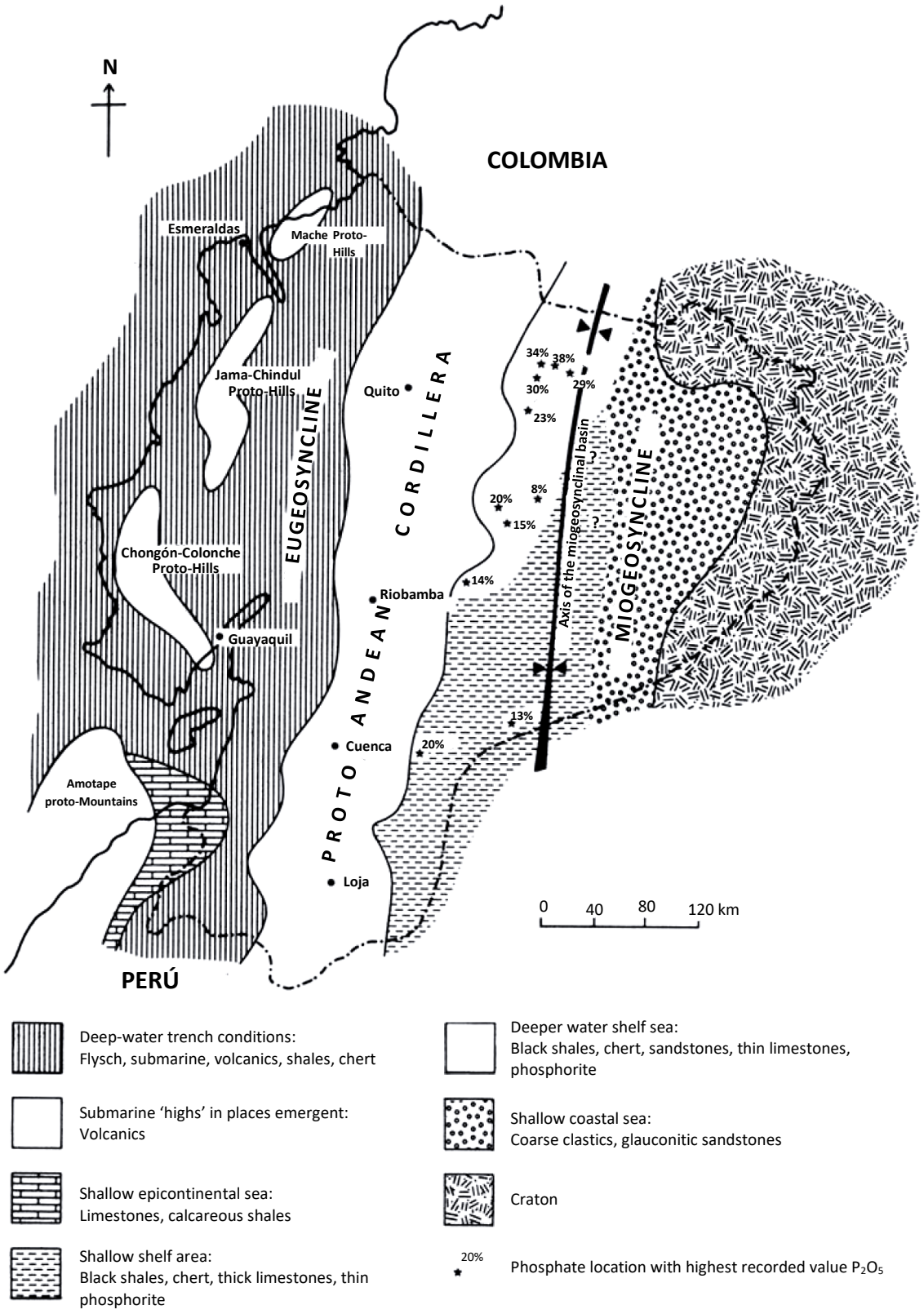


Fig. 8 Paleogeographic and lithofacies map (non-palinspatic) of Ecuadorian Upper Cretaceous, showing the supposed relationship between depositional basins and the proto-Cordillera. Reproduced from Wilkinson (1982)

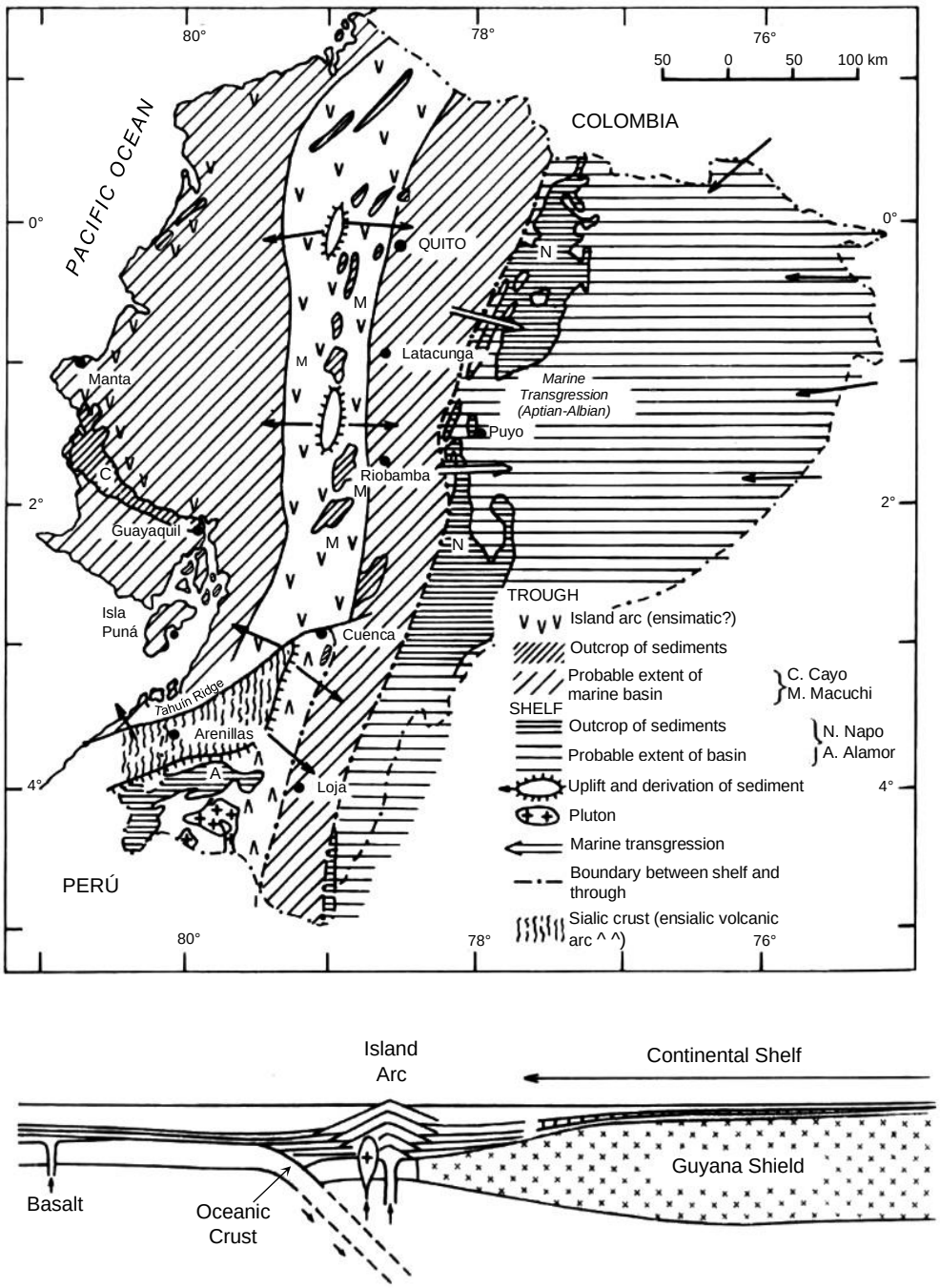


Fig 9. Paleogeographic and outcrop map of Ecuadorian Cretaceous (Aptian to Campanian) rocks with plate-tectonic interpretation. Reproduced from Kennerley (1980).

D. Tertiary: Pre-Oligocene

The absence of undoubted autochthonous Paleocene rocks in much of Ecuador suggests a period of Lower Tertiary deformation and/or uplift. This Incaic or Peruvian phase of the Andean Orogeny was developed strongly to the south, in Perú (Cobbing *et al.*, 1981). It was accompanied or succeeded by plutonism and volcanism (Sacapalca Formation) in the southern Sierra, and may have affected the Ecuadorian Cordillera belt (for example the metamorphism of the Paute Group Phyllites and Metavolcanics),

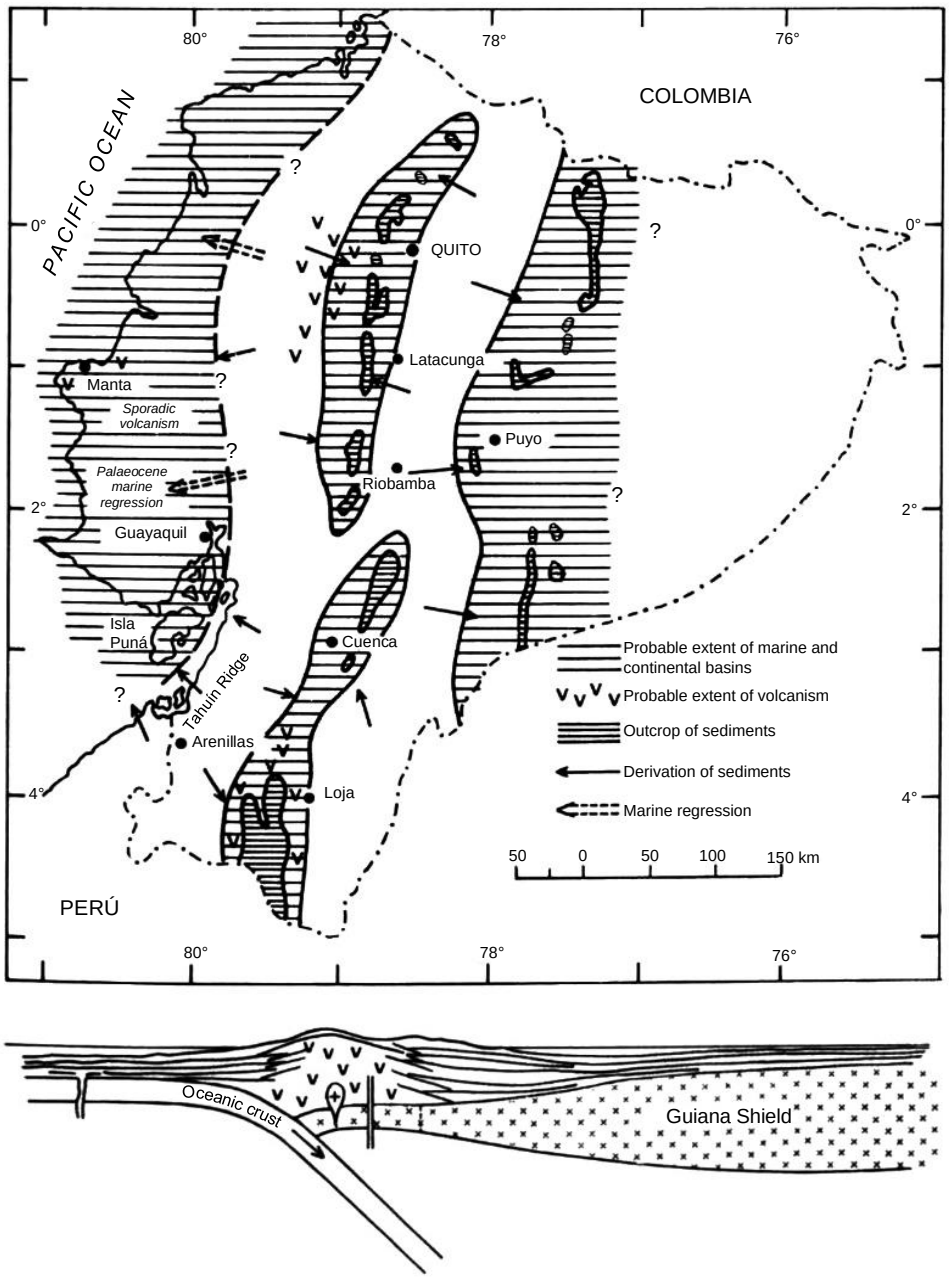


Fig 10. Paleogeographic and outcrop map of Maastrichtian-Paleocene rocks in Ecuador. Reproduced from Kennerley (1980).

The Lower Tertiary sedimentary fore-arc basins of the Costa continued to be separated from the back-arc Oriente Basin not only by the periodically inactive volcanic arc itself, but also by the emergent massif of the proto-Cordillera Real. Red-bed sedimentation (Tiyuyacu Formation) remained dominant in the Oriente; reef limestones, sometimes interbedded with volcanics, were developed in interarc basins in the middle Eocene (Unacota Formation), while turbiditic calcareous flysch derived from these fringing reefs was deposited in deeper-water fore-arc basins in the present coastal region (San Eduardo, Ostiones Limestones), During the Upper Eocene the coastal fore-arc basin was an unstable zone that developed three major (and several minor) depocenters (Fig. 11; reproduced from Kennerley, 1980). Allochthonous rocks of Cretaceous to Eocene age (Santa Elena Olistostromic Complex) were deposited chaotically in the deep Progreso Basin (Colman, 1970; Feininger and Bristow, 1980), while more normal turbiditic sedimentation continued in the Manabí Basin (San Mateo Formation) and in the Esmeraldas/Borbón Basin (Zapallo Formation).

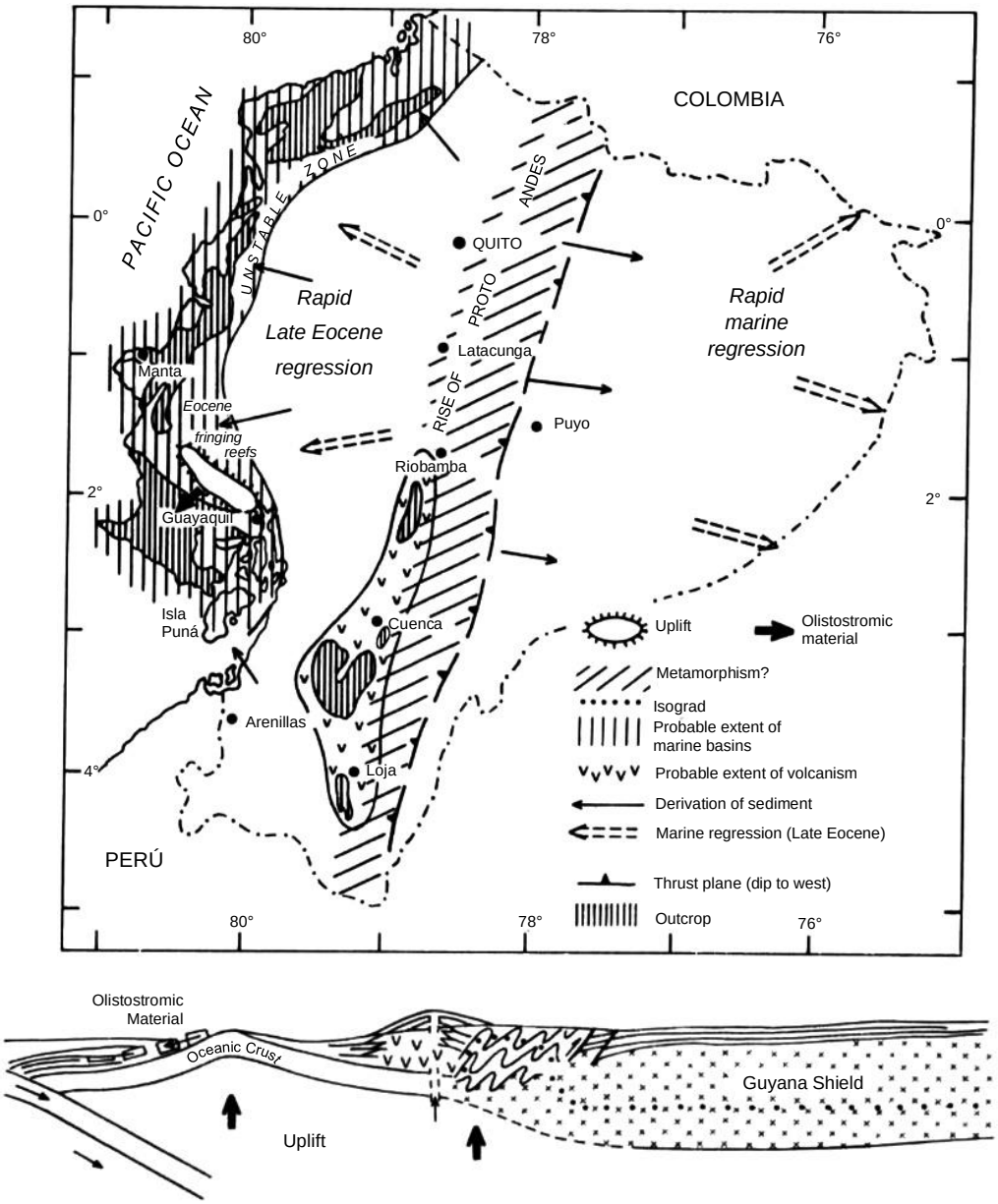


Fig 11. Distribution of Eocene-Oligocene rocks and paleogeographic reconstruction of the principal features of the late Eocene orogeny in Ecuador, with an interpreted westward "jump" in the position of the subduction zone. Reproduced from Kennerley (1980).

Late Eocene-early Oligocene diastrophism, correlated with the Quechua 1 phase of the Andean orogenic cycle in Perú (Cobbing *et al.*, 1981*),* principally affected the Sierra. Folding, perhaps accompanied by low-grade metamorphism, was important locally, and plutonism was widespread. Folding and fracturing of the Cretaceous-Lower Tertiary sequence occurred mainly during tectonic emplacement of the Macuchi Volcanic Arc against the proto-Cordillera. Clogging of the late Cretaceous-Paleogene subduction system led to the establishment of a new eastward-dipping Benioff zone further to the west (Fig. 11; reproduced from Kennerley, 1980) — the so called "jump" of the trench. Uplift and minor overthrusting commenced along the sub-Andean fault zone, contributing to the rise of the proto-Andes and the formation of freshwater intermontane, mainly Miocene basins, principally in southern Ecuador (Figs. 11 and 12; reproduced from Kennerley, 1980).

E. Tertiary: Post-Eocene Orogeny

Volcanism recommenced in the southern and central Sierra during the late Oligocene and continued in Miocene times (Saraguro Group, including Alausí, Saraguro, Loma Blanca, and Chinchillo Formations), but in the north there is no evidence for volcanic activity until the late Miocene-early Pliocene (Pisayambo Formation). Sedimentation occurred from the late Oligocene, throughout the Miocene and into the Pliocene, in the Progreso, Manabí, and Esmeraldas-Borbón depocenters, within the fore-arc basin of the Costa (Oligo-Miocene Tosagua and Viche Formations; middle to late Miocene Progreso Formation and Daule Group), as well as in the continental back-arc basin of the Oriente (Chalcana, Arajuno-Curaray, and Chambira Formations) (Fig. 1 and Fig. 12; reproduced from Kennerley, 1980). Miocene sediments were also deposited within intermontane basins in the progressively uplifted Cordillera (Bristow, 1973; Kennerley, 1973) and plutonism was evidently widespread along the Western Cordillera (Fig. 3). Much of the massive uplift of the Ecuadorian Andes is of late Neogene age, perhaps a final response to the Cretaceous to Miocene period of crustal thickening resulting from volcano-sedimentary deposition and associated underplating. In the sub-Andean back-arc foldbelt, late-stage deformation caused folding of Miocene sediments and also led to the Cutucú and Napo uplifts. Arching of the uplifted Sierra reintroduced a tensional regime in the late Miocene, that caused the development of the inter-Andean valley, bounded by reactivated normal faults (Figs. 4 and 5).

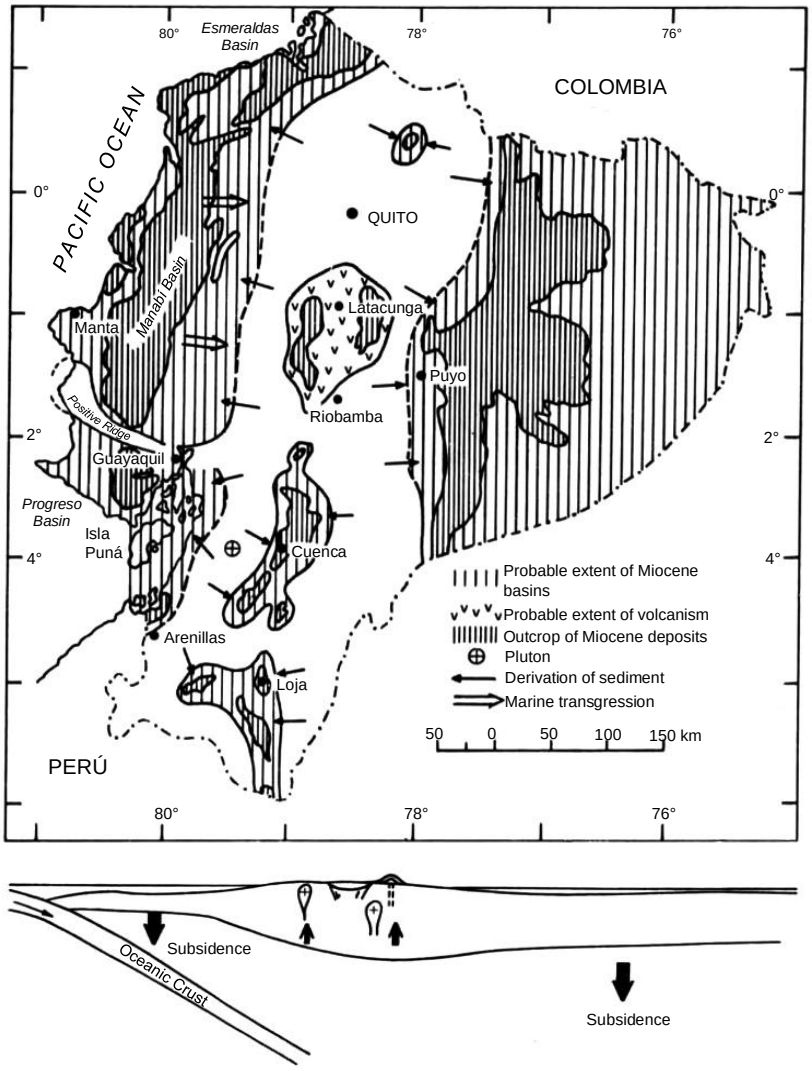


Fig 12. Outcrop map and paleogeographic reconstruction of the Ecuadorian Miocene. Reproduced from Kennerley (1980).

F. Plio-Quaternary

Continuing Plio-Pleistocene volcanism produced thick lava and pyroclastic cover sequences (Pisayambo and Tarqui Formations). Erosion in the Sierra led to the accumulation of thick laharitic, piedmont, and terrace deposits over the sub-Andean and western Oriente regions (Mera Formation and Mesa deposits). Uplift of the coastal hills, or mid-slope high (Evans and Whittaker, 1981), caused the depositional axis in the Costa to move eastward, closer to the Sierra, so that a thick Quaternary sequence (~1500 m) occupies the Guayas Basin (Fig 13; reproduced from Kennerley, 1980) and continues southward into the pull-apart Gulf of Guayaquil Basin, which is still undergoing active sedimentation.

Offshore, slow spreading of Neogene oceanic crust from the E-W (Galápagos or Cocos-Nazca) spreading axis built the thickened Carnegie Ridge: renewed, mainly submarine Plio-Quaternary volcanism in a region of crustal weakness led to the formation of the numerous shield volcanoes, whose summits are the Galápagos Islands. Subduction beneath the existing trench system is reflected by continuing volcanic activity in the Ecuadorian Andes to the present day with the development of two belts of major strato-volcanoes, the most currently active being to the east, along the Cordillera Real and in the sub-Andean zone (Hall, 1977), and by the deposition of thick (~50-80 m) ash deposits.

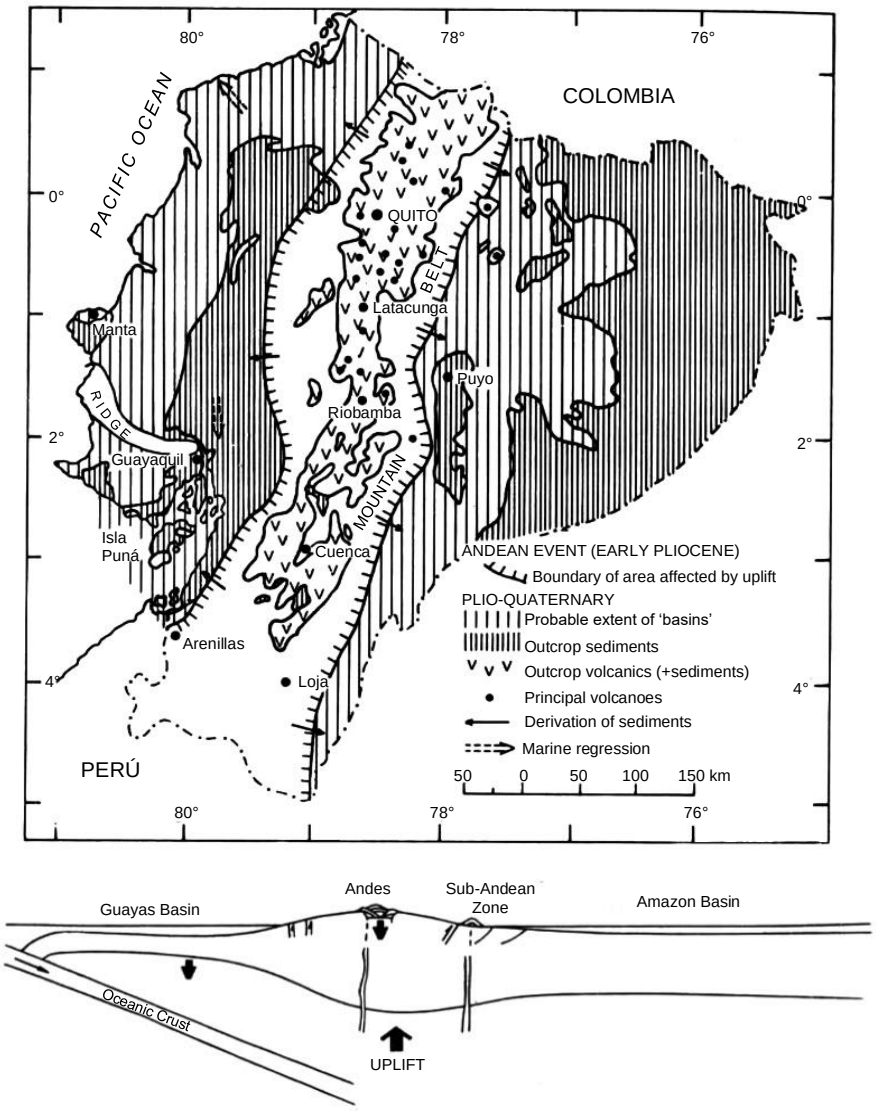


Fig 13. Outcrop of Plio-Quaternary rocks and principal features of early Pliocene Andean uplift in Ecuador. Reproduced from Kennerley (1980).

IV. SUMMARIZED TECTONIC INTERPRETATION

The geology of Ecuador exhibits both clear similarities and distinct differences compared with that of Perú to the south and Colombia to the north. In presenting a summarized tectonic interpretation it is necessary to draw a balance between the essential continuity of the Andean range with its flanking sedimentary basins or platforms, and the transverse segmentation that is also characteristic of the western margin of South America (Sillitoe, 1974; Cobbing *et al.*, 1981). Much of the Central and Northern Andes has a core of presumed ancient (Precambrian to Paleozoic) metamorphic rocks marginal to the Archean Craton. Precambrian and Paleozoic relics on the coastal side of the orogenic belt (Arequipa Massif, Amotape-Tahuín block) vary widely in age, but suggest that the Western Cordillera of the Andes, at least as far north as the Gulf of Guayaquil, and probably even further north (Esmeraldas-Pichincha Fault; Fig. 4), is underlain by a thickened continental lithosphere. Relationships in the Tahuín block suggest that parts of it might represent remnants of Precambrian greenstone terrain typical of other cratonic nucleii.

Northwest of the Guayaquil-Dolores Suture, isolated and inactive Mesozoic oceanic crust underlies western Ecuador and Colombia, an important difference between the Central Andes (Perú-Ecuador) and the Northern Andes (Ecuador-Colombia). The transverse Tahuín block and the major E-W faults (Jubones, Arenillas-La Palma; Fig. 4) are considered to be the northern limits of the loosely defined Huancabamba deflection separating these two major Andean segments, but it is the NNE-trending Guayaquil-Dolores suture, which is believed to follow the base (or western flank) of the Andes in most of Ecuador, that separates continental lithosphere to the east from old oceanic crust to the west (see Fig. 6).

The Guayaquil-Dolores Suture may represent an old dextral transform fault, probably linking with the Romeral Fault system in Colombia (Feininger and Bristow, 1980). It was evidently a complex crustal feature with numerous subsidiary (horsetail) faults (Jubones, Jambelí-Naranjal, Puná-Pallatanga, Milagro-Guaranda, Alluriquín-Mindo, and other faults) that sliced up the volcanic arc (Fig. 4). In northern Ecuador-southern Colombia the Cretaceous (Macuchi-Diabase Group) arc changes from ensialic to ensimatic, partly at another major tectonic break that could be superficially expressed by the transverse (NW-SE) Esmeraldas-Pichincha Fault (Fig. 4). Small, tectonically emplaced, ultrabasic bodies associated with a few of the NE trending major crustal fault structures may be slivers of ocean floor material (Hall and Calle, 1982) perhaps representing remnants of dismembered ophiolite (Juteau *et al.,* 1977). Gravity data suggest that in the Gulf of Guayaquil the total dextral displacement across the southernmost end of the Guayaquil-Dolores Suture is some 80-100 km (Shepherd and Moberly, 1981).

In the Paleozoic and early Mesozoic there was probably little to distinguish the Ecuadorian section of the proto-Andean belt from regions to the north and south. By middle or late Mesozoic time a miogeosynclinal basin or foreland platform was still undergoing periodic sedimentation on the west of the Guyana Shield. It was separated from a developing volcanic arc and deep (eugeosynclinal) fore-arc basin further to the west by structurally positive axes with cores of older metamorphic rocks, such as the Marañón Geanticline and Olmos Arch in northern Perú (Cobbing *et al.,* 1981; Fig. 6 therein), the proto-Cordillera Real in Ecuador (Fig. 8; reproduced from Wilkinson, 1982), the Garzón massif and ancestral Central Cordillera in Colombia. The change in the trend of these old positive axes from northwesterly in Perú to north-northeasterly in Ecuador and Colombia is believed to have resulted from uplift of Paleozoic (or older) sublinear to arcuate mobile belts.

By the Cretaceous, the western edge of the continental South American plate was bounded by Mesozoic oceanic crust that was being subducted northeastward beneath it. Along the Ecuadorian section of that trench system, the angle of convergence was highly oblique to the NNE-trending continental margin, resulting in the formation of a major transform fault (ancestral Guayaquil-Dolores Suture) at the plate boundary along and down which oceanic crust was "transducted".

Paleocene volcanism (Sacapalca Group) was restricted to the Huancabamba-Cariamanga Graben between the emergent positive highs of the Tahuín block and the proto-Cordillera in southern Ecuador, but was widespread in Perú (Older Calipuy Group, Cobbing *et al.*, 1981). North of the Gulf of Guayaquil convergence at the mid-Tertiary trench had virtually ceased, but volcanism did reoccur in the Eocene. The final phase of transduction of Mesozoic oceanic crust, which may have been partly overlain by Cretaceous (and Eocene?) volcanics, along the continental margin, perhaps led to the development of a series of dextral faults that sliced up the volcanic arc sequences and emplaced them during the late Eocene or early Oligocene against the deep-rooted metamorphic belt of the proto-Cordillera Real.

The late Eocene-early Oligocene phase of tectonism (Quechua 1 phase in Perú; see Cobbing *et al.*, 1981) was caused by the development of a new subduction system that partly resulted from clogging of the older subduction system and partly from a reorganization of crustal plates in the Pacific at this time (Herron, 1972). A more oceanward trench was developed, isolating the region of inactive (Mesozoic) oceanic crust that thus became accreted to the continental plate. Subduction at the new trench led to subaerial Oligo-Miocene volcanism (Saraguro Group) in the proto-Andean belt; contemporary erosion permitted thick clastic sedimentation to continue in the foreland back-arc basins as well as intermontane troughs.

Further reorientation of the Pacific plate system occurred in the late Neogene (Rea and Malfait, 1974; Lonsdale and Klitgord, 1978), indirectly resulting in Andean uplift (Quechua 2 phase in Perú), with a brief compressional phase causing thrusting to the east, especially in the back-arc fold/thrust belt. However, deformation and uplift by vertical tectonics in a tensional regime (arching of the Andean orogen) was dominant, and many of the old dextral shear zones were reactivated, mainly as faults with a vertical (normal) sense of movement, especially along the Inter-Andean valley between the two Cordillera.

In conclusion, it might be suggested that several important geotectonic differences between the Central Andes (Perú to southern Ecuador) and the Northern Andes (Ecuador-Colombia) can be ascribed, at least partly, to the change from normal convergent subduction of both the proto-Nazca and Nazca oceanic plates beneath the Central Andean sector, compared with transduction of the Mesozoic ocean floor (proto-Nazca plate) along the continental margin of the Northern Andean sector. Renewed convergence, originating from a trench further to the west, was therefore between Neogene oceanic crust and old, inactive, oceanic crust accreted to the continental South American plate.

The reason for the highly oblique convergence to the north of the principal bend (Huancabamba deflection) in the Andes may perhaps be found in the trend of Paleozoic (and older), as yet poorly defined, sublinear foldbelts around the southwestern and northwestern edges of the Precambrian cratonic nucleus of northern South America. This interpretation ultimately ascribes to the configuration of Paleozoic and Precambrian features such differences between the Central and Northern Andes as older metamorphic rocks and abundant Cretaceous/Paleogene plutons in the south compared with oceanic crust (ophiolite?) and no granitoid plutons to the north; destructive convergence in Perú compared with "accretion" in Ecuador-Colombia; eastward younging of magmatism, as a result of eastward migration of the Benioff zone, beneath the Central Andes, compared with possible westward younging of plutonism resulting from the development of a new subduction zone, further to the west, beneath the old oceanic plate and the Northern Andes.

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